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Estimating the L5/S1 flexion/extension moment in symmetrical lifting using a simplified ambulatory measurement system

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ABSTRACT

Mechanical loading of the spine has been shown to be an important risk factor for the development of low-back pain. Inertial motion capture (IMC) systems might allow measuring lumbar moments in realistic working conditions, and thus support evaluation of measures to reduce mechanical loading. As the number of sensors limits applicability, the objective of this study was to investigate the effect of the number of sensors on estimates of L5/S1 moments.

Hand forces, ground reaction forces (GRF) and full-body kinematics were measured using a gold standard (GS) laboratory setup. In the ambulatory setup, hand forces were estimated based on the force plates measured GRF and body kinematics that were measured using (subsets of) an IMC system. Using top-down inverse dynamics, L5/S1 flexion/extension moments were calculated.

RMSEs (Nm) were lowest (16.6) with the full set of 17 sensors and increased to 20.5, 22 and 30.6, for 8, 6 and 4 sensors. Absolute errors in peak moments (Nm) ranged from 17.7 to 16.4, 16.9 and 49.3 Nm, for IMC setup's with 17, 8, 6 and 4 sensors, respectively. When horizontal GRF were neglected for 6 sensors, RMSEs and peak moment errors decreased from 22 to 17.3 and from 16.9 to 13 Nm, respectively.

In conclusion, while reasonable moment estimates can be obtained with 6 sensors, omitting the forearm sensors led to unacceptable errors. Furthermore, vertical GRF information is sufficient to estimate L5/S1 moments in lifting.

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1. Introduction

Low-back pain (LBP) is often termed a pandemic of the modern world and it represents a large socioeconomic burden. In the Global Burden of Disease Study, LBP was ranked highest in terms of years lived with disability in Europe (Buchbinder et al., 2013). Mechanical loading of the low back has been shown to be an important risk factor for the development of LBP (Coenen et al., 2014, 2013; da Costa and Vieira, 2010; Kuiper et al., 2005; Norman et al., 1998).

Therefore, many studies have investigated the effect of ergonomic interventions on back moments (Davis and Marras, 2000; Faber et al., 2009, 2011, 2007; Hoozemans et al., 2008; Karwowski and Marras, 2003; Kingma et al., 2004; Marras et al., 1999). Measurements were mostly performed in a laboratory environment

equipped with advanced measurement systems such as force plates (FP) and optical motion capture (OMC) systems. Although valuable information can be obtained from these laboratory measurements, such research is expensive and ecological validity can be questioned. Furthermore, with the recent advancements in the development of assistive devices to reduce back moments during daily working conditions (de Looze et al., 2016), intervention studies in the field are getting more important. While some wearable measurement systems have been developed for ambulatory assessment of back loading (Ellegast et al., 2009; Freitag et al., 2007; Marras et al., 2010), these measurement systems are quite bulky. An alternative would be the use of wearable inertial/magnetic motion capture (IMC) system, consisting of small inertial measurement units (IMUs) measuring 3D segment motions. Such systems are less bulky and could even be worn under the clothes. Many studies have already shown the validity of IMC systems for measurement of kinematics (Cutti et al., 2008; Faber et al., 2013b; Godwin et al., 2009; Luinge and Veltink, 2005; Plamondon et al., 2007; Robert-Lachaine et al., 2017; Roetenberg et al., 2013). However, studies on validity of back moment estimation during lifting with IMC are, as of yet, scarce.

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To avoid the need for transducers between the hands and the objects handles (Marras et al., 2010), one could use bottom-up inverse dynamics. However, this requires accurate knowledge of the center of pressure location relative to the participant, which is problematic in combination with orientation based kinematics estimates from IMC systems (Faber et al., 2010). An alternative approach is to use top-down inverse dynamics, with hand forces derived from ground reaction forces (GRF's) and body accelerations instead of transducers at the hands. Faber et al., (2018) showed that hand forces can be estimated, with RMS errors below 16 N, based on the measured GRF and segment accelerations using an ambulatory measurement setup (IMC & Force shoes).

However, having IMUs on all body segments can still make it difficult to use such a system over a longer period or in a large number of subjects. A reduction of the number of sensors is important to make the systems more user-friendly and also more affordable, which is essential for the future use of such systems. However, it is not known how this affects back moment estimates.

Another practical limitation of current methods is that force shoes (FS) are still expensive and relatively heavy, which interferes with task performance. If horizontal forces can be ignored, this would allow the use of pressure insoles, instead of force shoes. Pressure insoles are known to provide reliable estimates of the vertical GRF during walking (Rouhani et al., 2010).

To allow for selecting the optimal number of sensors in an ambulatory system for the estimation of back moments, the objective of this study was to investigate the effect of reducing the number of IMC sensors on the accuracy of L5S1 extension moment estimates during symmetrical lifting. As a gold standard (GS), L5S1 moments were calculated using a state-of-the-art laboratory system, measuring GRFs with FPs and measuring full-body kinematics with an OMC system. In addition, we investigated the effect of using only the vertical component of the GRF on the estimated L5S1 moment for the optimal sensor set.

2. Methods

2.1. Subject and experimental procedures

Seventeen healthy subjects, 9 males and 8 females (age: 33.5 ± 12.0 years, mass: 69.9 ± 12.6 kg, height: 1.71 ± 0.10 m), participated in this study that was approved by the local ethics committee. After providing written informed consent, subjects were equipped with all instrumentation and, after some calibration measurements (see following sections), subjects walked to a box (10 kg; WxDxH = $33 \times 33 \times 27$ cm) and lifted it from the floor.

2.2. Instrumentation and data pre-processing

GRFs were measured with two Kistler FPs, one underneath each foot, at 200 samples/s (type 9286AA, Kistler Instrumente AG, Winterthur, Switzerland). An additional FP was used to measure the forces on the box during the pick-up phase. Force signals were bi-directionally low-pass Butterworth filtered with a cut-off frequency of 10 Hz. The reference hand forces were calculated using the box mass, acceleration of the box (measured using a cluster) and a separate force plate on which the box was located prior to the lift (Faber et al., 2018).

Full-body kinematics were measured with an Xsens IMC system at 120 samples/s (MVN, Xsens Technologies B.V., Enschede, the Netherlands) and with a Certus Optotrak OMC system at 50 samples/s (Northern Digital, Waterloo ON, Canada). All signals were resampled to 120 samples/s using linear interpolation. Kinematics were bi-directionally low-pass filtered with a second-order Butterworth filter at 5 Hz. Synchronization of FP and OMC was obtained

by data capturing from the same computer and software platform using a single start pulse. IMC data were synchronized based on the IMC and OMC resultant angular velocity of the head segment. For the IMC system, the standard full-body Xsens setup was used (Kim and Nussbaum, 2013; Roetenberg et al., 2013) consisting of 17 miniature inertial sensors (IMUs). IMC data were pre-processed using Xsens software (MVN Studio 3.0, Xsens technologies B.V., Enschede), providing a built-in anatomical human body model. For the OMC system, marker clusters were used to capture segment motion. For both the OMC and IMC systems, motion sensors (IMUs and marker clusters) were attached with straps to the pelvis, head, the upper arms, forearms, thighs, shanks, and feet. In addition, in accordance with the requirements of the built-in anatomical model, IMUs were placed on both scapulae, the sternum and hands; an additional marker cluster was placed on the posterior side of the thorax at the level of T9. Because most marker clusters were (rigidly) attached to the inertial sensors, only non-magnetic material was used in the clusters (verified with magnetic field IMU output).

2.3. Gold standard L5S1 moments

First, FP and OMC data were expressed in the same global coordinate system. Summing the GRFs measured by the two FPs provided the total GRF. For the OMC all 16 main body segments (feet, shanks, thighs, pelvis, abdomen, thorax, head, upper arms, forearms and hands) were tracked using marker clusters. Most segments were tracked by a dedicated marker cluster except for the hands and the abdomen segments which were attached to the forearm and thorax, respectively. For all segments, anatomical coordinate systems, center of mass (CoM) position, and inertial parameters were calculated based on anatomical landmarks that were related to the corresponding marker clusters using a probe with four markers (Cappozzo et al., 1995). L5S1 moments were calculated based on the GRFs and lower-body kinematics, using a bottom-up inverse dynamics model (Kingma et al., 1996) with improved anthropometric modeling (Faber et al., 2009) and were used as a gold standard (GS). To define a basic error level for inverse dynamics, moments were also calculated with a “top-down” approach (GS_td), using upper body OMC data and hand forces derived from box mass and acceleration, and subsequently compared with GS. Data processing was programmed in Matlab (MATLAB 2015b, The MathWorks, Inc., Natick MA, USA).

2.4. IMC based hand force and L5S1 moment estimation

For anatomical calibration (relating the IMUs to the corresponding segment coordinate systems) of the built-in MVN body-model, stature and segment lengths were provided as input into the MVN software and an upright calibration posture was recorded (N-pose) (Roetenberg et al., 2013). The Kinematic Coupling algorithm was enabled in the software, compensating for possible magnetic disturbances of the lower-body kinematics. The MVN defines the forward axis of the IMC global coordinate system as the direction of the local earth magnetic field. To align it with the OMC global coordinate system, data were rotated around the common vertical axis, such that the heading difference between the OMC and IMC pelvis averaged over time was zero. To estimate full-body segment CoM positions ($\mathbf{r_CoM}$) and inertial properties, bony landmark and joint position estimates (including the L5S1 joint) provided by the built-in MVN body-model were used as input to our 3D inverse dynamics model that we also used for the OMC system (same 16 body segments). MVN provides, based on the IMU inertial recordings, for each segment the angular velocity (ω), angular acceleration (α) and the linear acceleration of the origin ($\mathbf{a_origin}$) of the segment (usually the proximal joint) in the earthbound coordinate

system. To calculate the segment CoM accelerations (\mathbf{a}_{CoM}) the following equation was used for each segment:

$$\mathbf{a}_{\text{CoM}} = \mathbf{a}_{\text{origin}} + \alpha \times (\mathbf{r}_{\text{CoM}} - \mathbf{r}_{\text{origin}}) + \omega \times (\omega \times (\mathbf{r}_{\text{CoM}} - \mathbf{r}_{\text{origin}}))$$

Subsequently, estimated hand forces (\mathbf{HF}_{est}), i.e., the forces exerted by the hands on the box handles, were calculated in the global coordinate system based on the GRFs, the subject's body mass (m_{body}) and the mass (m_i) and $\mathbf{a}_{\text{CoM}_i}$ of each included body segment i :

$$\mathbf{F}_{\text{HFest}} = \mathbf{F}_{\text{GRF}} + m_{\text{body}} \mathbf{g} - \sum_{i=1}^q (m_i \mathbf{a}_{\text{CoM}_i})$$

where \mathbf{g} is the gravitational vector ($\mathbf{g} = [0 \ 0 \ -9.81]$) and q is the total number of included body segments (Faber et al., 2013a). IMC L5S1 moments were estimated based on the upper-body segments (IMC_{upper}) using the “top-down” calculation in our inverse dynamics model (Kingma et al., 1996). A global equation of motion (rather than a segment-by-segment calculation) was used as described by Hof (1992). This implies that no assumption was needed with regard to distribution of hand forces over the left and right hands.

2.5. Sensor set reduction

In order to test to what extent the number of IMU's influences the accuracy of the L5S1 moment estimate, four sensor sets were tested (Table 1; Fig. 1). Set A was the full sensor set; In set B, the sensors on the thighs, hands and head were removed; in set C, the sensors on the shanks were additionally removed and in set D, the sensors on the forearms were additionally removed. Note that the shanks and thighs, if included, were only relevant for HF estimation, not for “top-down” inverse dynamics.

For the HF estimation in reduced sensor sets, simple assumptions were used to estimate accelerations of segments without sensors: for the feet (sensor sets B, C & D) & hands (D) accelerations were set at zero, whereas the acceleration of the shanks (C) was estimated to be $[0, 0, 1/4]$ times the acceleration of the pelvis for the x, y and z direction, respectively. The same method was used for the thighs (B & D) where the acceleration was estimated to be $[0, 0, 3/4]$ of the pelvis acceleration. Note that, the pelvis acceleration is the summation of the accelerations of the lower leg and upper leg. Based on a simple leg model with equally long upper and lower legs and CoM locations half way these segments, we estimated the vertical acceleration of the lower leg to be $1/4$ and that of the upper leg to be $3/4$ of the vertical acceleration of the

pelvis. The acceleration of the head (B, C & D) was assumed to be equal to the acceleration of the trunk and the accelerations of the forearms (D), were assumed to be equal to the accelerations of the upper arms.

For the top-down L5S1 moment calculation, masses of the excluded segments were added to their proximal segments. For sensor sets B & C, hands were rigidly attached to the forearms. The mass of the head was added to the thorax segment to create a new thorax-head segment (B, C & D) of which the \mathbf{r}_{CoM} , \mathbf{a}_{CoM} and inertia tensor were recalculated. For sensor set D, masses of the hands and forearms were simply added to the upper arms, as no reasonable assumption on forearm CoM location relative to the upper arm is possible. The estimated HF was assumed to have its point of application in the most distal included arm segment, i.e. \mathbf{r}_{CoM} of the hands (A, B, C) or the elbows (D). Finally, a sensor set E was created, which was a copy of sensor set C except that for the HF estimation only vertical GRF information was used.

2.6. Data reduction and statistics

The correspondence between the outcomes of the gold standard and the IMC sensor sets was quantified for the flexion/extension component of the L5S1 moment only. For the flexion/extension time series, root-mean-squared errors (RMSEs) and coefficients of determination (R^2) were calculated. Furthermore, absolute flexion/extension peak and cumulative squared moment values (integral of the squared moments (Coenen et al., 2012)) from the time series of the GS and the IMC sensor sets (A, B, C, D, E) were extracted. To determine whether the sensor sets influenced the estimated L5S1 moment (RMSEs, peak and cumulative) a one-way repeated measures ANOVA was performed. When significant main effects were found, sensor set effects were further explored using planned comparisons between adjacent sensor sets. A significance level of $p < .05$ was used.

3. Results

Based on the RMSEs of the IMC sensor set A, two participants (34 Nm & 37 Nm) were marked as outliers ($>3 \times \text{SD}$) and therefore excluded from further analysis. In-depth analysis showed that these errors were caused by large fluctuations in trunk COM, most likely due to wobbling of an insufficiently fixed sternum IMU. In the remaining participants, a Repeated Measures ANOVA showed a main effect of sensor set on RMS error, peak moments, and cumulative moments squared (Table 2; all $p < .001$). These effects will be outlined in more detail below.

Table 1

Summary of the segments measured in the different sensor sets. The column HF shows which segments are used to estimate the hand force whereas the ID TD column shows the segments used for the top-down inverse dynamics analysis. Included segments are shown in light gray whereas excluded are shown in dark gray.

| | Sensor set A | | Sensor set B | | Sensor set C | | Sensor set D | |
|------------|--------------|-------|--------------|-------|--------------|-------|--------------|-------|
| | HF | ID TD | HF | ID TD | HF | ID TD | HF | ID TD |
| Feet | | | | | | | | |
| Shanks | | | | | | | | |
| Thighs | | | | | | | | |
| Pelvis | | | | | | | | |
| Trunk | | | | | | | | |
| Head | | | | | | | | |
| Upper arms | | | | | | | | |
| Forearms | | | | | | | | |
| Hands | | | | | | | | |

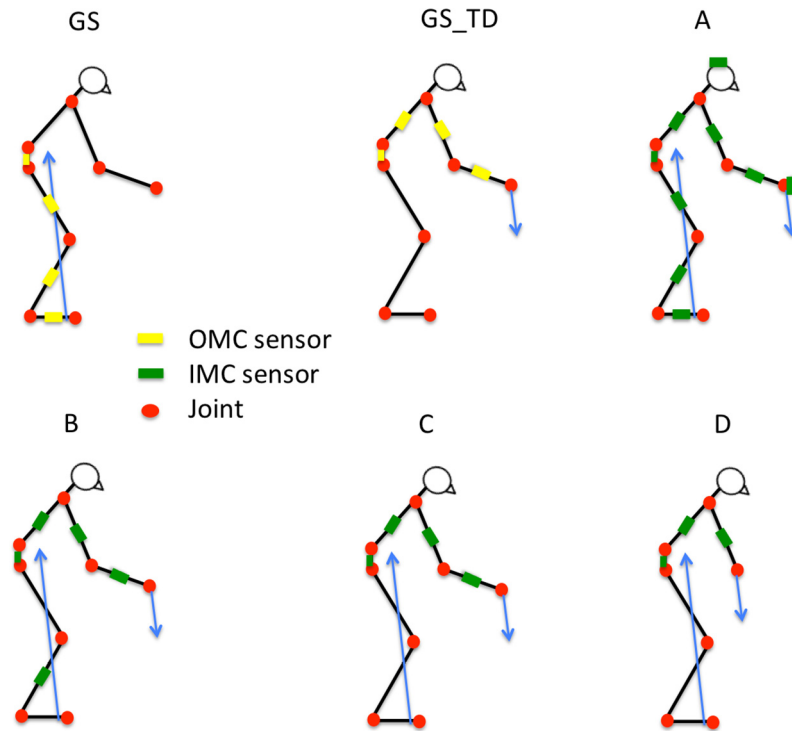


Fig. 1. Optical representation of the two OMC systems (GS & GS_TD) and the four IMC systems (A, B, C & D).

Table 2

Repeated measures ANOVA and subsequent planned comparisons (P and F values) with sensor set (GS, A, B, C & D) as independent variable. Bold values indicate significant differences ($p < 0.05$).

| | Main effect | | Planned comparisons | | | | | | | |
|---------------------------------|------------------|-------------|---------------------|-------------|--------------|-------------|------------------|-------------|------------------|--------------|
| | Sensor set | | GS vs. A | | A vs. B | | B vs. C | | C vs. D | |
| | p | F | p | F | p | F | p | F | p | F |
| RMS L5S1flex/ext moment | <0.001 | 79.6 | <0.001 | 38.2 | 0.005 | 10.8 | <0.001 | 79.3 | <0.001 | 34.7 |
| PEAK L5S1flex/ext moment | <0.001 | 65.8 | <0.001 | 24.7 | 0.720 | 0.13 | 0.597 | 0.29 | <0.001 | 217.3 |
| CUM L5S1flex/ext moment | <0.001 | 68.2 | <0.001 | 49.0 | 0.963 | 0.02 | <0.001 | 50.4 | <0.001 | 55.9 |

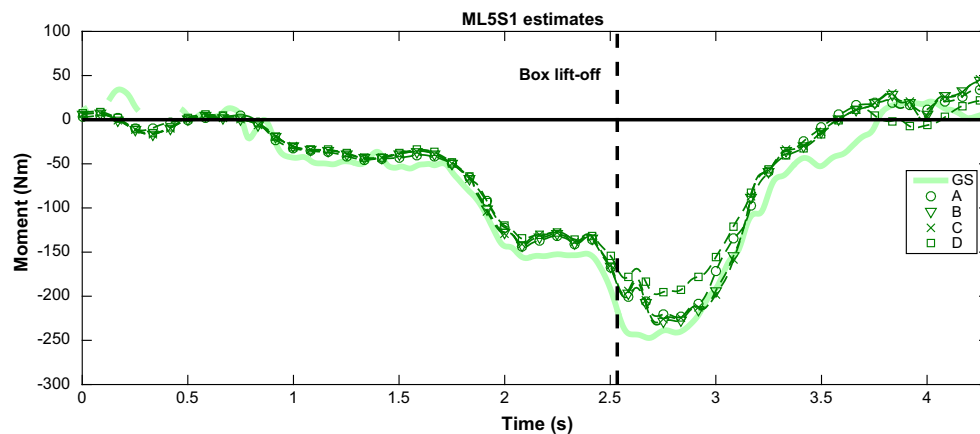


Fig. 2. Typical example of a symmetrical lifting trial, showing the L5S1 moment (flexion/extension) time series calculated based on the reference laboratory system (GS), and the IMC based sensor sets (A, B, C & D). Negative values imply external flexion moments. The vertical dashed line shows the time instant when the box was fully supported by the hands.

3.1. L5S1 moment time series

A typical example of the lifting trial shows that, especially during peak loading, omitting more sensors resulted in increasing

underestimation of peak L5S1 extension moments (Fig. 2). Planned comparisons showed a significant ($p < .001$) increase in RMS errors for each reduction of the sensor set. However, the overall correspondence between the L5S1 moment estimates from the GS

(OMC & FP) and the IMC based sensor sets was good (Fig. 3), with R^2 -values above 0.93 and average RMSerrors below 31 Nm (about 15% of the peak L5S1 extension moment) for all sensor sets (A, B, C & D). As expected, the difference between Gold Standard “bottom-up” (GS) and “top-down” (GS_td) was smallest, with an average RMSerror of 8.4 Nm (4.0% of the peak L5S1 extension moment). The full sensor set (A) showed good correspondence with the GS with an average RMSerror of 16.6 Nm. Neglecting information from the feet, upper legs, head and hand sensors (B) led to an increase of the RMSerror to on average 20.5 Nm. Subsequent removal of shank (C) and forearm (D) sensors increased the RMSerror to on average 22.0 Nm and 30.6 Nm, respectively.

3.2. Peak and cumulative squared L5S1 moments

Using the full IMC sensor set (A), peak flexion/extension moment was estimated to be 17.7 Nm lower ($p < .001$) compared to the GS estimate. Sensor set reduction steps to B and C resulted in small changes in peak moments, but these changes were not significant. However, the most simplified sensor set (D) resulted in a substantial underestimation of the peak moment by on average 49.3 Nm compared to the GS (23%), and this differed significantly from sensor set C.

For the cumulative moment squared, the full sensor set already underestimated the moment by almost 20% (Fig. 4). Further reduction of the sensor set to B and C resulted in minor but significant changes. For the most simplified sensor set (D) the underestimation significantly increased up to almost 37.1% for sensor set (D).

3.3. Effect of only using the vertical component of the GRF

Surprisingly, when ignoring the horizontal component of the GRF in sensor set C (resulting in sensor set E), the RMSerror relative

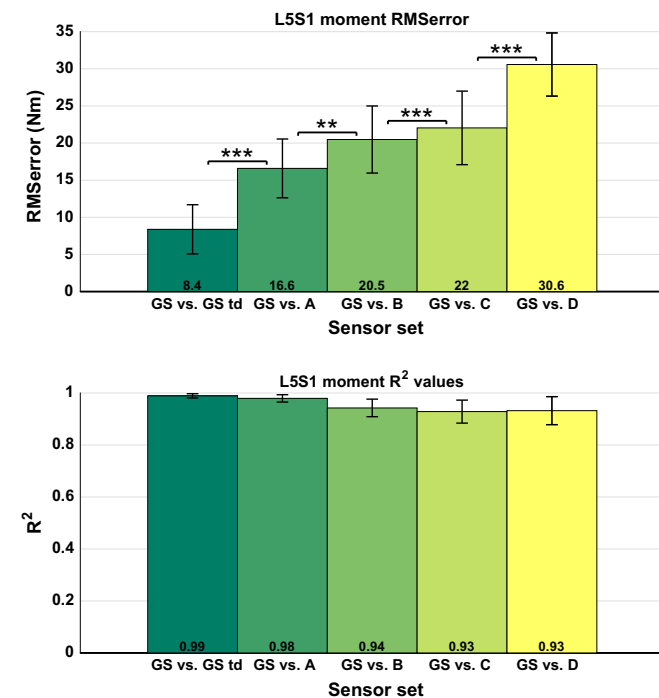


Fig. 3. L5/S1 moment time series correspondence (RMSerrors & R^2 -values) between the L5/S1 moments calculated based on the reference laboratory system (GS & GS_td) and the full (A) and stepwise reduced (B, C & D) IMC based sensor sets. A significant difference between two adjacent bars is indicated either with * ≤ 0.05 , ** ≤ 0.01 or *** ≤ 0.001 . The error bars indicate the standard deviation.

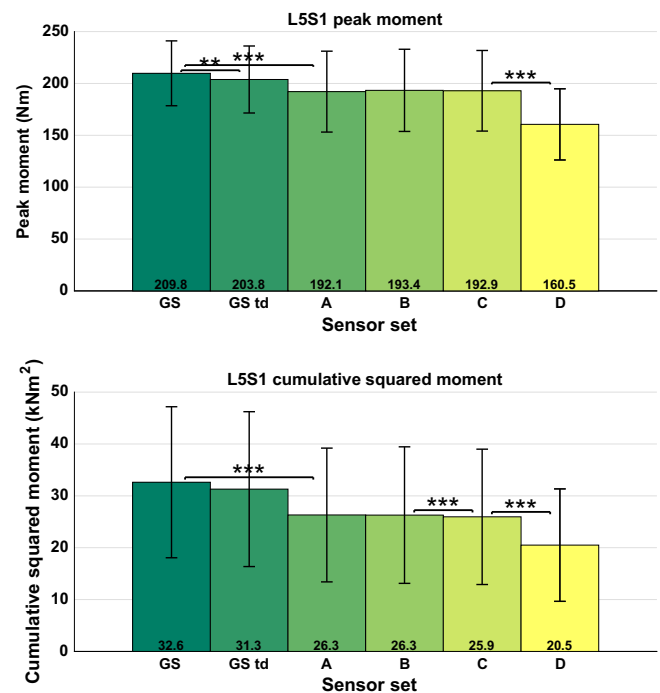


Fig. 4. L5/S1 peak and cumulative moments calculated based on the reference laboratory system (GS & GS_td) and the full (A) and stepwise reduced (B, C & D) IMC based sensor sets. A significant difference between two adjacent bars is indicated either with * ≤ 0.05 , ** ≤ 0.01 or *** ≤ 0.001 . The error bars indicate the standard deviation.

to the GS decreased ($p = .001$) from 22 Nm (C) to 17.3 Nm (E) on average (Fig. 5). Furthermore, the R^2 -values did not change ($p = .485$) between sensor set C (0.93) and E (0.94), the peak moment increased ($p = .02$) from 192.9 Nm (C) to 196.8 Nm (E) and the cumulative moment squared increased ($p < .001$) from 25.9 kNm² (C) to 28.6 kNm² (E). Consequently, all outcome measures indicated a decreased rather than an increased error when ignoring the horizontal component of the GRF.

4. Discussion

The present study investigated the effect of using several simplified IMC setups on estimates of L5S1 moments. In addition, we investigated the effect of using only the vertical component of the GRF on the estimated L5S1 moment for the selected optimal sensor set. RMSerrors (Nm) were lowest (16.6) with the full set of 17 sensors and increased to 20.5, 22 and 30.6, for 8, 6 and 4 sensors. Absolute errors in peak moments (Nm) ranged from 17.7 to 16.4, 16.9 and 49.3 Nm. When horizontal GRF were neglected for 6 sensors, RMSerrors and peak moment errors decreased from 22 to 17.3 and from 16.9 to 13 Nm, respectively.

4.1. Sensor set selection

Based on the data presented, sensor set C can be considered optimal regarding accuracy and simplicity. Peak moment estimates were not significantly different between sensor sets A & B and B & C. Neglecting kinematic information of the forearms (D) had a large impact due to the need of knowing the point of application of the external load. Assuming this to be the elbow resulted in substantial underestimation of the moment arm of the load relative to L5S1 (see Fig. 2). However, kinematic information of the hands, thighs, lower legs and head can be neglected without substantially compromising the accuracy of the L5S1 flexion/extension moment esti-

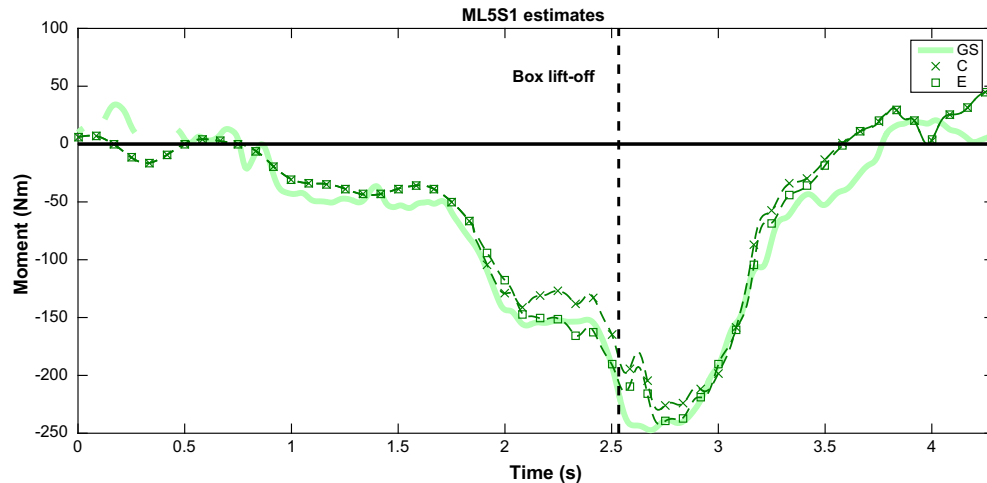


Fig. 5. Typical example of a symmetrical lifting trial, showing the L5S1 moment (flexion/extension) time series calculated based on the reference laboratory system (GS), IMC based sensor set (C), and the same set with the vertical ground reaction force omitted. Negative values imply external flexion moments. The vertical dashed line shows the time instant when the box was fully supported by the hands.

mate. For sensor set C, differences with the GS were acceptable with average errors of 9%, 10% and 20% for the peak, RMSerror and cumulative moment, respectively. The cause of the bigger error for the cumulative load is the squaring of the moments, which amplifies differences. Surprisingly, ignoring the horizontal component of the GRF did not increase the error measures for sensor set C, but rather decreased it: compared to GS average errors were 6%, 8% and 12% for the peak, RMSerror and cumulative moment squared, respectively. This shows that for moment estimation in symmetrical lifting tasks, the horizontal component of the GRF can be neglected, which would suggest that pressure insoles can be used instead of force plates, if these measure the vertical GRF with sufficient accuracy. It may well be that results would be less favorable for tasks involving large horizontal forces such as pushing and pulling.

The current RMSerrors between GS and the IMC full sensor set (A) of 16.6 Nm seems comparable to previous studies (Godwin et al., 2009; Kim and Nussbaum, 2013) using inertial sensors during a lifting task (15–20 Nm). In a study without hand loads, using trunk bending only, absolute moment errors were somewhat smaller (10 Nm) but relative errors were similar. We are not aware of any previous studies estimating the effect of reduced sensor sets on the L5S1 moments.

4.2. Sources of error

The present results show that L5S1 moments were systematically underestimated with the IMC system, even with the full sensor set (A). The total estimation error can be divided into different parts: (1) A minor part is the orientation error of the IMU's which were around 1 degree (Faber et al., 2013b). (2) Errors in the estimation of the hand forces will obviously result in errors in the L5S1 moment estimation. For sensor set C, hand force error, at the moment of peak hand force, was around 10 ± 9 N, multiplied with the moment arm at that instant resulted in a moment estimation error of around 8 Nm. However, this is only due to the error in the estimation of the hand force, the biggest error comes from accumulation of positional errors leading to substantial underestimations of moment arms of distal upper body segments with respect to L5S1. The error in the moment arms between L5S1 and the most distal segment (hands) was, at the instant of peak moment, on average 10 ± 4 cm. Besides being due to accumulation

of position errors, this may also be due to the fact that an IMC system relies on segment orientations rather than positions (Faber et al., 2010). As a result, translations of the arm relative to the trunk are underestimated (Robert-Lachaine et al., 2017), so that the moment arms of hand forces relative to the L5S1 joint are underestimated when flexing the shoulder.

With the OMC system, we were able to quantify the shoulder translations by comparing shoulder joints estimates based on the trunk and upper arm segments. Shoulder translations varied between 5 and 12 cm across subjects. This approach shows that indeed errors may be attributed to not capturing the shoulder translation. Due to the systematic nature of this error, a general correction might be possible in order to reduce some of the errors. However, this would require extensive validation and is beyond the scope of this article.

The simple assumptions of neglecting the horizontal acceleration terms in the legs didn't have large implication for the estimated hand forces. As a matter of fact putting the horizontal accelerations at zero instead of one times the horizontal pelvis accelerations, reduced the error in the y direction substantially. Putting the vertical acceleration of the legs back to its measured value led also to an increase of the average peak error from 10 to 14 N.

4.3. Limitations

It should be mentioned that in this study only healthy males and females participated. System performance and even sensor set choice may be different in, for example, obese people due to differences in anthropometry and soft tissue motion (Forner-Cordero et al., 2008). Furthermore, in the current experiment only a symmetrical lifting (no twisting of the torso) task at normal speed was used. Different lifting speeds and asymmetrical movements may lead to different results. In addition, while ignoring the horizontal GRF did not negatively affect our outcomes, this might be different for pushing and pulling tasks, or lifting tasks with much larger horizontal forces. In this perspective, the present study can be seen as a proof of concept showing that a reduced sensor set is still able to measure L5S1 flexion/extension moments during symmetrical lifting tasks. Future studies should test this concept in a broader range of subjects and tasks and ultimately in a field setting.

4.4. Conclusion

This study showed that with a reduced sensor set, with IMUs only at the pelvis trunk, upper arms and forearms, accurate estimates of the L5/S1 flexion extension moments can be made during a symmetrical lifting task. Furthermore, it was shown that the horizontal component of the GRF in these tasks can be ignored, which would open up the possibility for using pressure insoles, if these measure the vertical GRF with sufficient accuracy. Thus, an inertial motion capture system is a potential candidate for ambulatory assessment of back loading in field settings.

Conflict of interest

The authors state that there is no conflict of interest to report.

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